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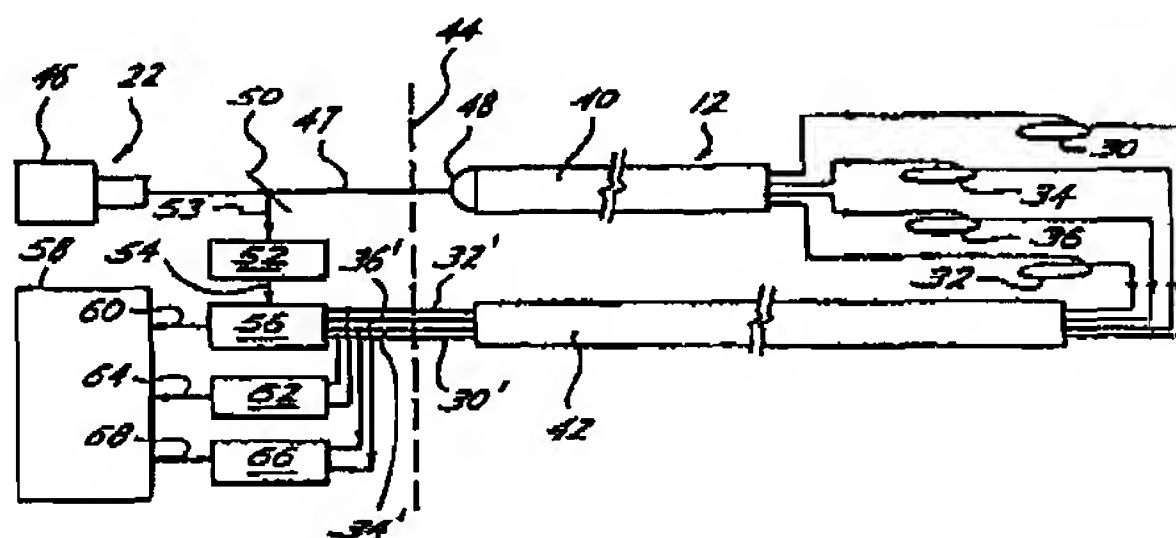
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**Marine seismic sensor.**

A hydrophone streamer (12) that includes several arrays (20) of optical fiber pressure sensors. Each array (20) consists of at least three sensors (30, 32, 34) symmetrically disposed around the inside of the streamer skin (26) to form a vertically-disposed array. Each sensor modulates a coherent light beam (47) in accordance with the instantaneous ambient water pressure. The output signals of the sensors include an AC component due to seismic waves and a DC component due to hydrostatic pressure difference between the sensors of an array. Means (22) are provided to resolve the AC (62, 66) and DC (58) components to determine the arrival direction of the received seismic waves.



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Marine Seismic Sensor

1           This invention relates to the use of  
pressure sensors to determine the direction of propagation  
of seismic pressure waves in a body of water.

5           In seismic exploration at sea, a plurality of  
pressure sensors are encased in a long tubular plastic  
streamer which may extend for one or two miles. A ship  
tows the streamer through the water at a desired depth.  
The earth layers beneath the sea are insonified by suitable  
means. The sonic waves are reflected from the earth layers  
10 below, to return to the surface of the water in the form of  
pressure waves. The pressure waves are detected by the  
pressure sensors and are converted to electrical signals.  
The electrical signals are transmitted to the towing ship  
via transmission lines that are contained within the  
15 streamer.

          The reflected sound waves not only return directly  
to the pressure sensors where they are first detected, but  
those same reflected sound waves are reflected a second  
time from the water surface and back to the pressure  
20 sensors. The surface-reflected sound waves of course, are  
delayed by an amount of time proportional to twice the  
depth of the pressure sensors and appear as secondary or  
"ghost" signals. Because the direct and surface-reflected  
sound waves arrive close together in time - a few

1 milliseconds - they tend to interfere with one another. It  
is desirable therefore to determine the direction of  
propagation of the sound waves so that the upward- and  
downward-propagating waves may be more readily sorted out  
5 during data processing.

It is possible to position two individual sensors  
in a fixed vertical array. It would of course then be easy  
to identify the direction of propagation of the sonic waves  
from the measured difference in time that a particular  
10 wavelet arrives at the respective sensors that make up the  
vertical array. See for example, U.S. Patent 3,952,281.  
That method however requires two separate hydrophone  
cables. Since such cables cost about a half-million  
dollars each, that course of action would be decidedly  
15 uneconomical.

Assuming that sufficiently compact sensors could  
be obtained, it would be possible to mount a substantially  
vertical array of sensors inside the same streamer, a few  
inches apart. But a seismic streamer cable twists and  
20 turns as it is towed through the water. If a substantially  
vertical sensor array were to be mounted inside the  
streamer, there would be no way to determine which one of  
the sensors in the array is "up", assuming conventional  
detectors are used. It is also important to be able to  
25 identify unwanted waves travelling horizontally from  
scatterers within or near the bottom of the water layer.

As is well known, a water-pressure gradient exists  
between two points spaced vertically apart in a body of  
water. If then, there were some way that the hydrostatic  
30 pressure gradient between two vertically-disposed detectors  
could be measured, the uppermost detector of an array could  
be identified.

Conventional marine detectors or hydrophones use  
piezo-electric ceramic wafers as the active element. The

1 wafers are generally mounted to operate in the bender  
mode. Transient pressure changes due to acoustic waves  
flex the wafers to generate an AC charge current. The  
wafers are also sensitive to hydrostatic pressure. But the  
5 DC charge due to hydrostatic pressure leaks off rapidly  
through associated circuitry. Therefore a differential DC  
component due to a hydrostatic pressure difference of the  
detector signal cannot be detected.

A preferred embodiment of the present invention seeks to  
10 provide a plurality of arrays of pressure sensors in an inexpensive  
streamer that is capable of detecting AC transient pressure  
signals due to seismic waves and to identify their direction of  
arrival in three dimensional space with reference to the vertical  
whose direction is sensed by measuring the DC bias due to the  
15 vertical hydrostatic pressure gradient.

In accordance with such an embodiment, a  
plurality of optical-fiber, sensor arrays are mounted  
interiorly of a seismic streamer at a like plurality of  
sensor stations distributed at intervals along the  
20 streamer. Each sensor array consists of a set of at least  
three and preferably four coils of monomodal optical fiber  
that act as pressure sensors. If four coils are used, the  
four sensor-coils are mounted ninety degrees apart around  
the inner surface of the streamer skin. A laser or LED  
25 launches a coherent beam of monochromatic light into each  
set of sensor coils via an input transmission line.  
Transient and static pressures at the sensor coils modulate  
the light beam. The modulated output light beam from each  
sensor coil of a set is delivered to a multiple-input photo  
30 detector where the beam from each individual sensor coil is  
separately combined with a reference beam. The  
photo-detector converts the resulting optical beat signals  
to AC electrical signals representative of the polarity and  
amplitude of transient seismic signals impinging upon the  
35 sensor coils.

1            Preferably, separate modulated output light beams  
are combined with each other at a photo-detector which  
converts the phase difference between the light beams to a  
DC electrical signal having a magnitude representative of  
5   the DC bias due to the hydrostatic pressure gradient  
between the sensor coils. The AC seismic signals and the  
DC bias signals are transmitted to a data processor where  
the direction of propagation of incoming seismic waves may  
be resolved.

10           Preferably, the laser, photo-detectors, data  
processor and other optical and electronic circuitry are  
mounted aboard a towing ship. The input and modulated  
output light beams are transmitted to the sensor coils  
through optical-fiber bundles.

15           Preferably, each set of sensor-coils is provided  
with a separate laser or LED, photo detectors, and a beam  
splitter to provide a reference beam all mounted together  
in a single module at the sensor stations. The modulated  
light beams are resolved as to the AC and DC signal  
20   components which are converted to electrical signals. The  
electrical signals are transmitted to the data processor by  
wire line.

For a better understanding of this invention,  
reference may be made to the appended detailed description  
25   and the drawings wherein:

Figure 1 shows a boat towing through the water a  
streamer containing a plurality of optical-fiber sensor  
coils at corresponding sensor stations;

30           Figure 2 is a longitudinal cross section of the  
streamer at a typical sensor station;

Figure 3 is a cross section of the streamer along  
line 3-3; and

Figure 4 illustrates schematically, the optical  
circuitry.

1 Referring now to Figure 1, there is shown a ship  
10 towing a seismic streamer 12 through a body of water  
14. Streamer 12 is towed by an armored lead-in 16 which  
5 includes stress members, armoring and it may include one or  
more optical fiber bundles. When not in use, lead-in 16  
and streamer 12 are stored on a reel 18 at the stern of  
boat 10. Streamer 12 contains several sets 20 of  
optical-fiber sensor coils, one set per sensor station. As  
will be seen later, each set 20, includes three but  
10 preferably four such sensor coils. An optical equipment  
package 22 such as a laser, photo detectors, optical  
couplers and data processing equipment is mounted aboard  
ship 10. Equipment package 22 will be described at length  
later. A tail buoy or drogue 24 marks the end of the  
15 streamer 12. One known system, which however employs only  
one sensor per sensor station is shown in U.S. Patent  
4,115,753.

20 Streamer 12 consists essentially of a long tubular  
plastic skin made of polyvinyl chloride, polyurethane or  
the like, about three inches in diameter, closed at both  
ends. A complete streamer may be several thousand feet  
long but, for convenience in handling, it may be divided  
into a number of detachable sections. The streamer is  
filled with a substantially incompressible fluid  
25 transparent to seismic waves for coupling external  
pressures to the internally-mounted sensors. A stress  
member 28, usually a stainless steel cable, is threaded  
through the entire streamer to prevent rupture due to  
towing stress.

30 Referring to Figure 2 which is a longitudinal  
cross section of a portion of the cable at a sensor  
station, and Figure 3 which is a cross section at 3-3 of  
Figure 2, a sensor unit 20 consists of a set of at least  
three and preferably four optical-fiber sensor coils 30,



1 32, 34, 36 having an elongate configuration that are  
mounted inside skin 26 of streamer 12 parallel to the  
longitudinal axis. For sake of example, let it be assumed  
that there are four such coils. There are thus two pairs  
5 of sensor coils such as 30 and 32, 34 and 36. The members  
of each pair are mounted diametrically opposite to one  
another at 90° intervals, parallel to and as far away from  
the longitudinal axis of the streamer as practicable.  
Preferably the sensor coils are held in place by a plastic  
10 spider such as 38. Since the longitudinal axis of the  
streamer, when under tow, is substantially horizontal, the  
set of sensor coils forms a two-dimensional array having a  
vertical extent comparable to the inner diameter of the  
tube 26.

15 The sensor coils are fashioned from many turns of  
a monomodal glass fiber having a low light loss per unit of  
length. The dimensions of the coil and the number of turns  
depend upon the total length of optical fiber required.

It is well known that when an optical fiber is  
20 subjected to a compression, the index of refraction and/or  
the elongation changes. The phase shift between a light  
beam transmitted through a reference fiber and a beam  
transmitted through an active fiber subjected to  
compression is a function of the fiber length and the  
25 incremental change in the index of refraction and/or  
elongation or both. See for example, U.S. Patent  
4,320,475. For a practical pressure sensor, a fiber length  
of about 100 meters is required for the active fiber. For  
an elongated fiber coil loop about two meters long and two  
30 or three centimeters wide, about 25 turns would be  
necessary. It is necessary for the sensor coils to be  
mounted so that flexing or movement of the streamer skin  
will not distort the shape of the coils. Such distortion  
would of course introduce spurious signals to the system.

1 Two optical-fiber bundles 40 and 42 are threaded  
through the streamer and the respective spiders that  
support the sensor coils at each sensor station. Bundle 40  
is the outbound transmission link through which is launched  
5 an input light beam from a transmitting laser (not shown in  
Figure 2), to each sensor coil. Bundle 40 may be a single  
fiber with provision for coupling its transmitted light to  
each sensor coil or it may consist of a bundle of single  
fibers, one fiber being assigned to each sensor coil. In  
10 effect the coils have an essentially common light-beam  
input. For example, coil 36 has an input fiber lead 35 and  
an output fiber lead 37. The other coils have similar  
input and output leads. Because of the small size and  
light weight of the fibers, several hundred fibers can be  
15 packaged into a single bundle without becoming unduly bulky.

Fiber bundle 42 is the return transmission link  
for the sensor-coil output light beams. There is one  
output fiber for every sensor-coil. Therefore, four output  
fibers are necessary to service each sensor station. The  
20 free end of fiber bundle 42 that exits the streamer and  
lead-in at the ship, is coupled to optical processing  
circuitry now to be described.

The preferred method of operation of this  
invention may be gleaned from Figure 4 which schematically  
25 illustrates the optical processing circuitry. In Figure 4,  
all components to the left of dashed line 44 may be mounted  
on ship 10 as part of the processing package 22.  
Components to the right of dashed line 44 are made a part  
of streamer 12.

30 A laser or LED 46, operating preferably in the  
near infra-red portion of the spectrum launches a coherent  
light beam 47 into an optical coupler 48 that couples the  
light beam into the fiber or fibers that make up fiber  
bundle 40. The optical coupler 48 acts as an essentially



1 common input to the fiber bundle. The light is transmitted  
to the optical-fiber sensor coils where the light beams are  
modulated by transient seismic pressure waves and the  
ambient hydrostatic pressure. The modulated light beams  
5 return from the sensor coils, through fiber bundle 42, to  
processing unit 22. In Figure 4, only one typical sensor  
station is shown for simplicity, but it should be  
understood that fiber bundles 40 and 42 may be extended to  
service additional sensor stations.

10 In optical equipment package 22, a beam splitter  
50 directs a part 53 of the laser beam 47 into a suitable  
optical delay module 52 whose output becomes a reference  
beam 54. Optical delay module 52 retards beam 53 to match  
the length of the optical path between beam splitter 50 and  
15 the sensor coils 30, 32, 34, 36 of any given sensor  
station. A different delay module is associated with each  
of the plurality of sensor stations to compensate for the  
differing optical path lengths.

The modulated light beams return from sensor coils  
20 30, 32, 34, 36 through corresponding optical fibers 30',  
32', 34', 36'. The beams are individually combined with  
reference beam 54 by suitable photo-detectors, of any  
desired type, in multiple-input combiner module 56. The  
resulting beat frequency is converted to an AC electrical  
25 wave train representative of the transient pressure  
variations due to seismic waves. The electrical signals  
from the four sensors may be multiplexed into data  
processor 58 over line 60.

The DC bias, due to a water-pressure gradient,  
30 between the light beams in a first pair of diametrically  
opposite sensor coils such as 30 and 32 is measured by  
combining the two output light beams in a photo-detector  
62. The phase shift between the two beams is converted to  
a DC electric bias signal having sign and magnitude that is

1 delivered to data processor 58 over line 64. Similarly the  
DC bias between the light outputs of the second pair of  
coils, 34 and 36, is measured by photo detector 66. The  
resulting electrical output is transmitted to data  
5 processor 58 over line 68. From the magnitude of the two  
bias signals, the physical orientation of the sensor coils,  
relative to a vertical plane, can be resolved by well known  
mathematical algorithms. In data processor 58, since we  
know now of the physical orientation of the sensor coils in  
10 the vertical plane, the directions of propagation of the  
respective seismic pressure waves can be resolved by  
measuring the arrival-time differences of a seismic wavelet  
at the respective sensor coils of the array.

In the above discussion, I have disclosed a means  
15 for resolving the magnitude and direction, within a  
vertical plane perpendicular to the axis of the cable, of  
seismic waves propagating through a fluid medium such as  
water. The direction of propagation in three-dimensional  
space can of course be determined by measuring the time  
20 difference between the arrival times of the same seismic  
wavelet at two or more selected consecutive sensor stations  
along the cable by means well known to the art. The  
longitudinal time differences may be combined with the  
vertical time differences by simple vector addition to  
25 resolve the direction of propagation in three axes.

I have described my invention in terms of a  
specific configuration. However, those skilled in the art  
may consider other equally effective arrangements without  
departing from the scope of the appended claims. For  
30 example, each of the individual sensor arrays could be  
provided with its own laser, beam splitter, photo-detectors  
etc., all of which could be included in individual modules  
mounted in the streamer at each sensor station. The  
electrical analogs of the measured phase shifts of the

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- 1 modulated and reference light beams would be transmitted to data processor 58, aboard ship 10, by wire line.

Claims

1           1. A method for marine seismic exploration  
C H A R A C T E R I Z E D   B Y: disposing a plurality of  
pressure sensor arrays within and along an elongate member,  
each array consisting of at least three pressure sensors  
5   displaced radially in said member in three different  
directions in a plane that is orthogonal relative to the  
elongate member; towing said member in a substantially  
horizontal configuration through a body of water at a  
preselected depth; detecting seismic waves with said  
10   sensors; converting said detected seismic signals to  
corresponding electrical signals; separating the AC and DC  
components of said electrical signals; and resolving said  
AC and DC components to determine the direction of  
propagation of said seismic signals with respect to  
15   three-dimensional space.

2. The method of claim 1 C H A R A C T E R I Z E D  
B Y: substantially uniformly distributing said pressure  
sensors of each array around the longitudinal axis of said  
elongate member and positioning the sensors comprising each  
20   array at substantially the same longitudinal location along  
said member.

3. The method of claims 1 or 2, C H A R A C T E R -  
I Z E D   I N   T H A T: the sensors of each array are  
optical-fiber pressure sensors for receiving and modulating  
25   a coherent monochromatic light beam, thereby providing a  
plurality of output light beams that are modulated in  
response to transient pressure variations due to seismic  
waves and to hydrostatic pressure, deriving AC signal  
components representative of said transient pressure  
30   variations by separately combining said modulated light  
beams with a reference light beam; for each sensor array,  
combining the separate modulated light beams with each

1 other to derive DC signal components representative of the  
magnitude of the hydrostatic pressure differential between  
said sensors.

4. The method of any one of claims 1-3 C H A R A C-  
5 T E R I Z E D B Y: measuring the horizontal and vertical  
arrival-time differences of said transient pressure  
variations at selected horizontally and radially disposed  
sensors making up the respective sensor arrays; combining  
said AC components, said DC components and said arrival  
10 times for resolving the direction of propagation, in  
three-dimensional space, of the detected seismic waves.

5. An apparatus for practicing the method of any  
one of claims 1-4 C H A R A C T E R I Z E D B Y: an  
elongate member 12 for containing at least one  
15 pressure-sensor array 20, said array including at least  
three radially disposed pressure sensors such as 30, 32,  
34, means 40 for transmitting an actuating signal to said  
sensors 30, 32, 34 of array 20, to produce data signals  
related to sensed pressure transients due to seismic waves,  
20 a signal recording system 22, and means 42 for transmitting  
said so produced data signals to said recording system 22.

6. The apparatus of claim 5 C H A R A C T E R-  
I Z E D B Y: a plurality of sensor arrays are distributed  
along the longitudinal axis of said elongate member 12 at  
25 preselected intervals, each said array 20 including four  
optical fiber sensors 30, 32, 34, 36, said sensors being  
uniformly distributed radially about the longitudinal axis  
of said elongate member 12 in a plane substantially  
perpendicular to the longitudinal axis of said member, said  
30 actuating-signal transmitting means 40 being an optical  
fiber and said data-signal transmitting means 42 including  
at least one optical fiber.



1           7. The apparatus of claim 6 C H A R A C T E R -  
I Z E D    B Y: a laser 46 for launching a coherent  
monochromatic beam of radiation into transmission means 40  
for modulation by the sensors of the respective arrays 20  
5   in response to pressure variations due to seismic waves and  
to differential hydrostatic pressure; a detector means 56  
in recording system 22 for receiving separately the  
modulated light beams from the respective sensors 30, 32,  
10 34, 36 of each array 20 over data transmitting means 42 and  
for combining said modulated light beams with a reference  
light beam 54 to determine the AC signal components of said  
modulated light beam that are due to pressure transients  
caused by seismic waves.

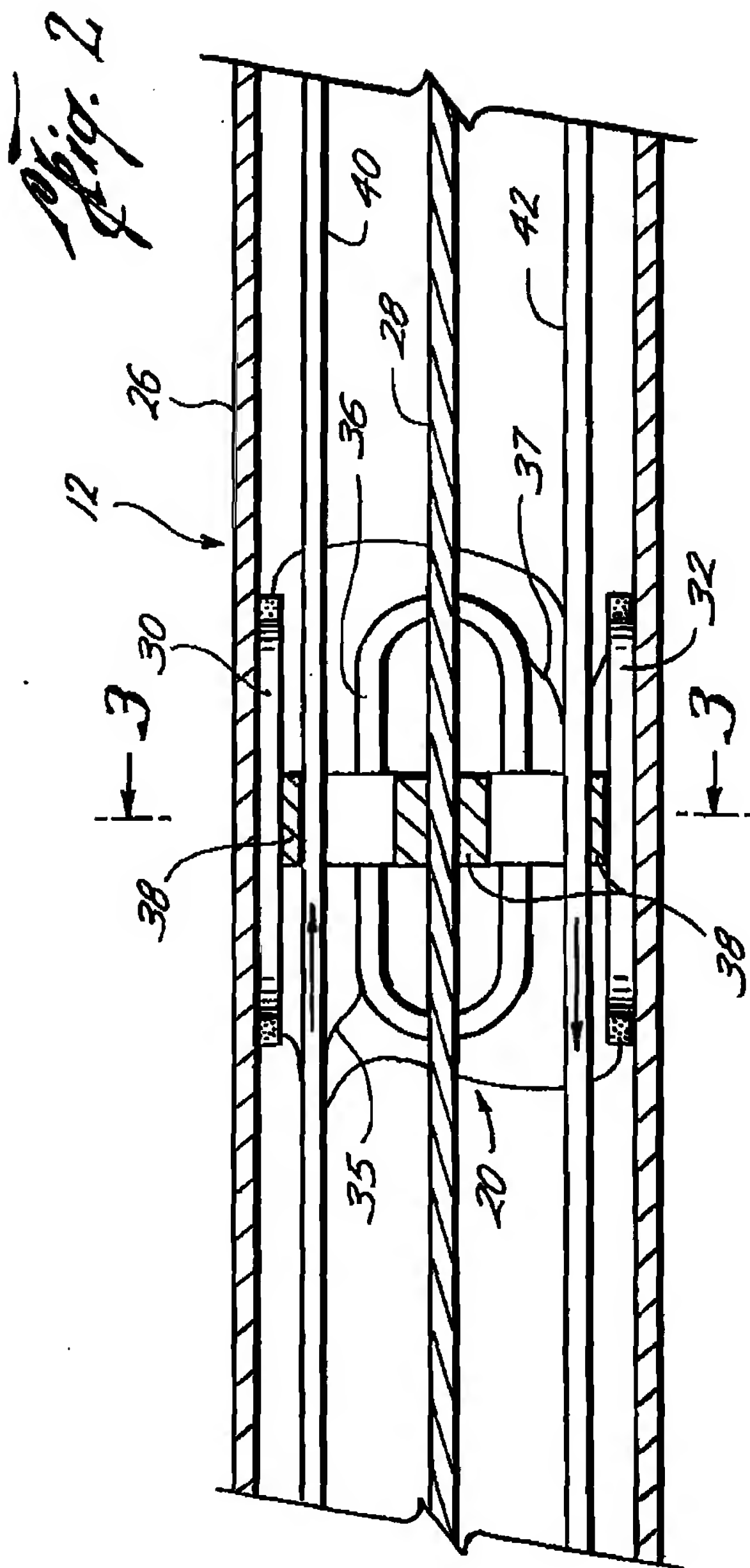
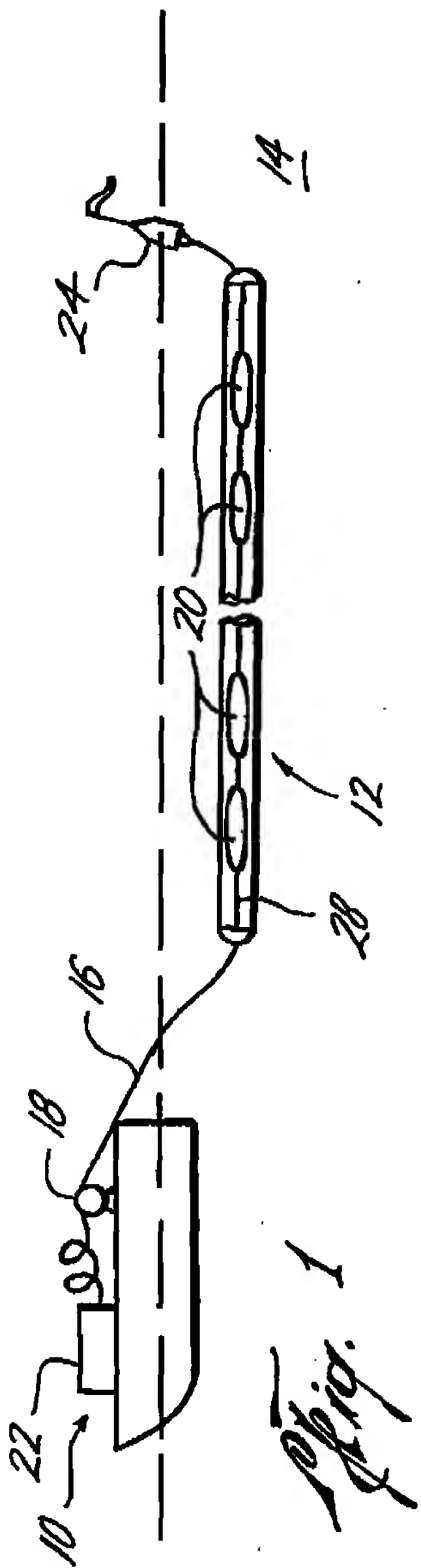
15           8. The apparatus according to claim 7 C H A R A C -  
T E R I Z E D    B Y: photo detectors 62 and 66 for  
combining respectively the modulated light beams from  
sensors such as 30 and 32 and from sensors such as 34 and  
36 to determine the DC components of said modulated light  
beams that are representative of differential hydrostatic  
20 pressure at the respective sensors.

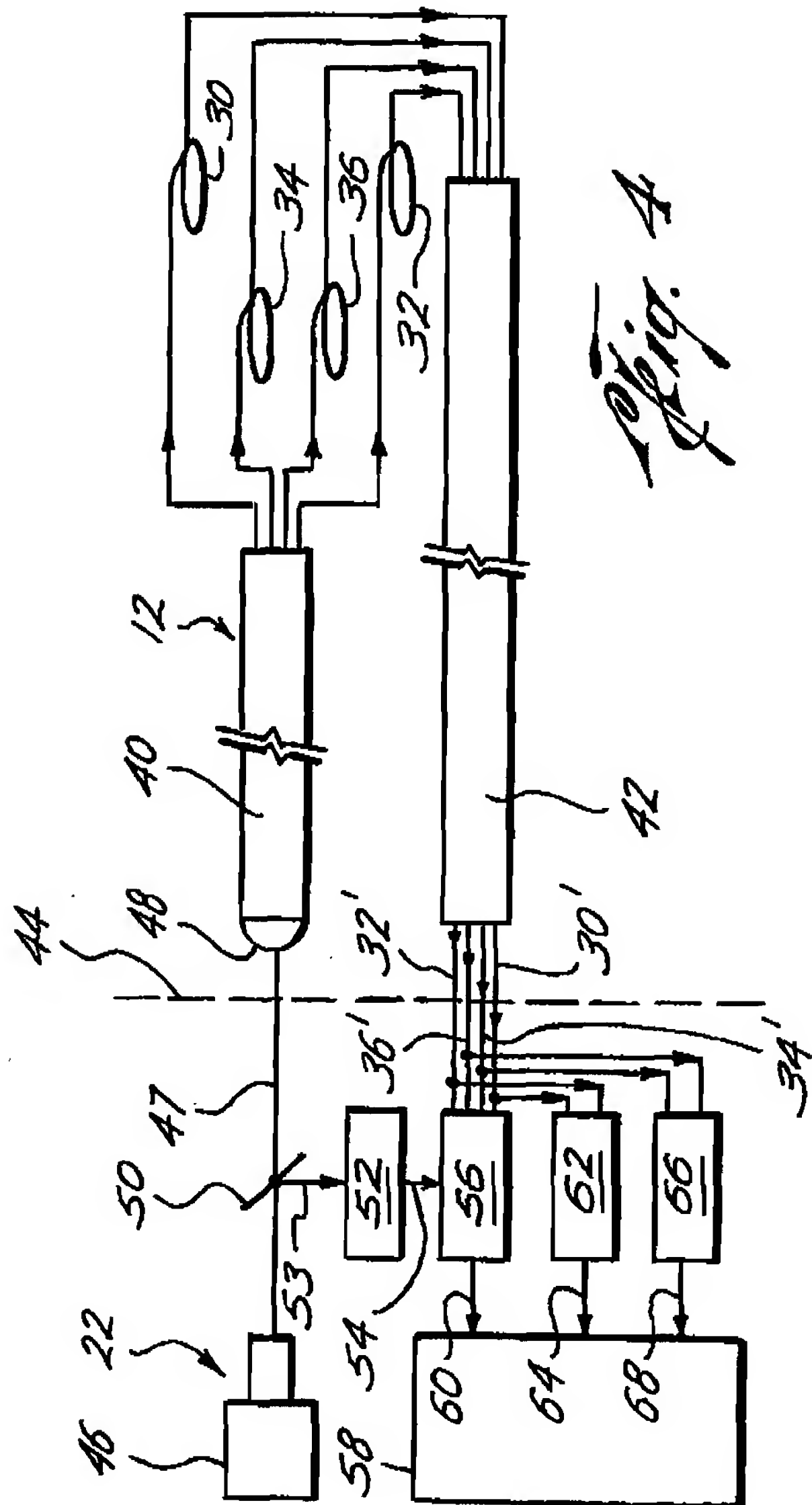
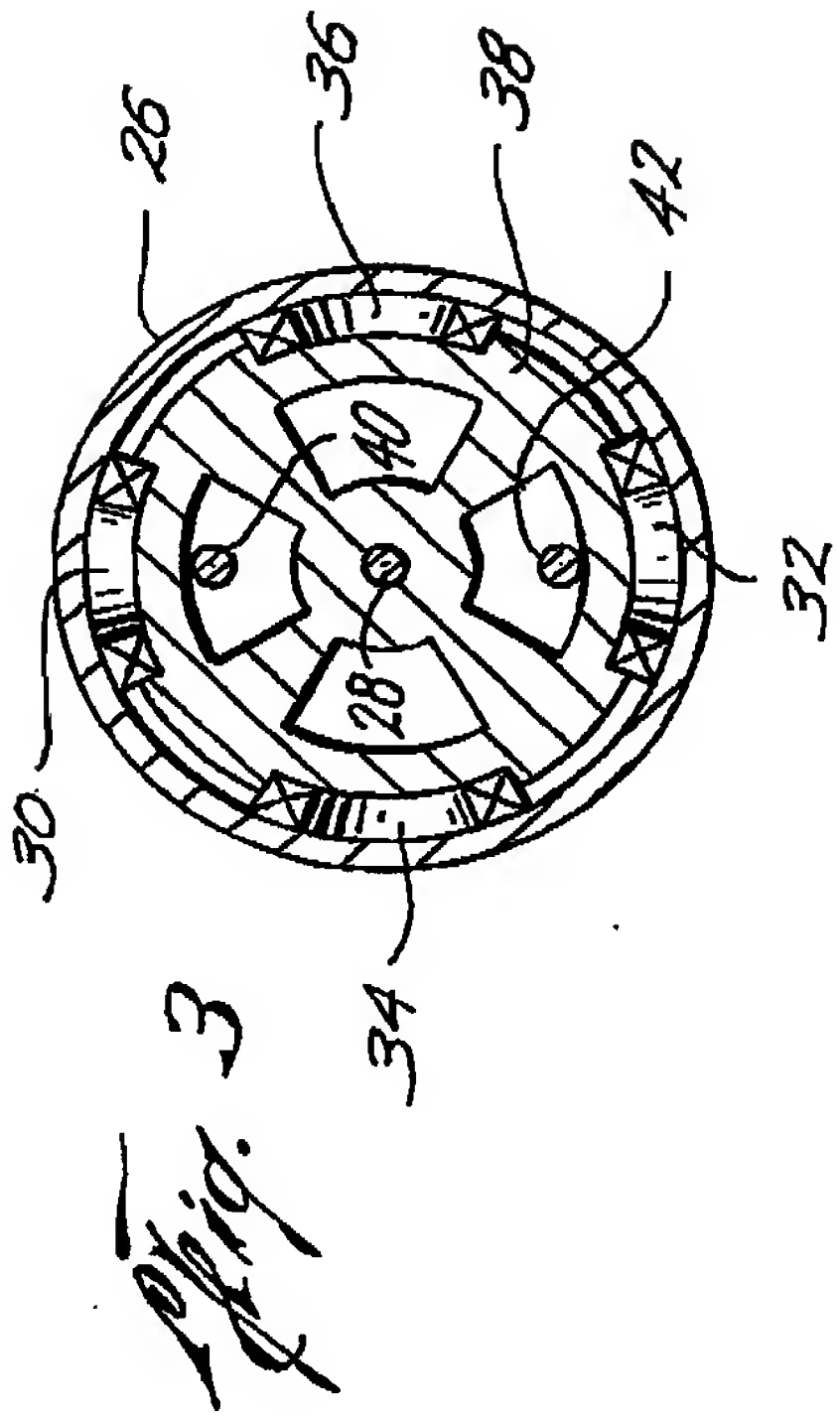
25           9. The apparatus according to any one of claims 6-8  
C H A R A C T E R I Z E D    I N    T H A T: all of the  
sensors of all of the respective arrays have a common  
source of coherent radiation, that each sensor provides a  
separate modulated output beam, and that said data  
transmission means 42 consists of a bundle of separate  
optical fibers.

30           10. The apparatus according to any one of claims  
6-8

C H A R A C T E R I Z E D    I N    T H A T: all of the  
sensors within a given array have a common radiation source  
but each separate array has a separate radiation source,  
all of the sensors of all of the arrays providing separate  
modulated output beams.

1            11. The apparatus according to any one of claims  
5-10 C H A R A C T E R I Z E D I N T H A T: said  
elongate member 12 is a closed container having a volume of  
fluid contained therewithin for coupling the  
5 internally-mounted sensors with external pressure  
variations.







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# EUROPEAN SEARCH REPORT

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Application number

EP 84 30 6368

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	US-A-4 078 223 (B.B.STRANGE)  * Abstract; column 4, line 63 - column 5, line 35; claim 1; figures 2,5 *	1,2,5,11	G 01 V 1/20 G 01 H 9/00
A	US-A-3 148 351 (P.G.BARTLETT) * Column 3, lines 22-64; figures 1,2 *	1	
A	GB-A-2 083 221 (MOBIL OIL) * Abstract; figure 3 *	1	
A	CA-A-1 124 384 (MAJESTY IN RIGHT OF CA.) * Claims 1,3,5,6,14,15; figures 6,7 *	1	
A	EP-A-0 027 540 (HYDROACOUSTICS INC) * Claims 6-10; figures 8,9 *		
			TECHNICAL FIELDS SEARCHED (Int. Cl.4)
			G 01 V G 01 H G 10 K
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 05-06-1985	Examiner HAASBROEK J.N.
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	